Metallic pressure vessels failures

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Abstract

First of all, this paper concentrates on the identification of possible explosion scenarios involving metallic vessels. Based on the review of scientific literature as well as internal work, an evaluation of the role of wall material is put forward. This work is supported by a summary of significant accident cases based on both recent INERIS experience and external sources. Given the importance of the vessel failure mode during these accidents, this paper subsequently focuses on the mechanical modeling of tank failure. This step consists in reviewing available models for metallic cracking and the way they handle with the phenomenon of fluid discharge.

1. Introduction

Metallic vessels are of common use in the industrial field: they can be operated at very different pressure levels to store or to transport gas or pressurized liquid (such as LPG or LNG), to dry, or as steam boiler... etc. As a consequence, metallic enclosures are also widely involved in many accidents, sometimes with catastrophic consequences.

Although the causes of vessel accidents have been widely investigated, the exact role of some parameters still remains unclear. Therefore, forecasting the effect of such an accident on the neighborhood of the vessel is usually achieved with the help of handbooks, that sometimes overestimate effects, such as the ones of BLEVE. Dynamic crack formation and fracture propagation in the enclosure wall are among those well identified, but unfamiliar parameters.

Two main causes need to be considered concerning the vessel rupture. The first one is a fast rise in pressure inside the vessel due to an overfilling or an overheating of the vessel. This overheating is itself caused by an external fire, a runaway reaction or an internal explosion. For this reason, the pressure inside the vessel exceeds the dynamic pressure limit of rupture. The second cause of rupture is a reduction of the vessel strength caused by corrosion, overheating, material defect or external impact. This second aspect will not be investigated in this paper. A sudden rise in pressure, which leads to the ruin of the container at the post-ultimate time, can be due to a human mistake, an uncontrolled chemical reaction, a physical phenomenon like BLEVE, a physical and chemical phenomenon like a rise in mass, an explosion, ... Table I brings together a panel of accidents with their causes, resulting phenomena and consequences on both material and human.

Accidents diversity hinders the clear forecast of the event and its effects on the vessel environment. Enclosure wall cracking is an important parameter to study: the conditions of its start, the way and the speed at which it propagates can give essential information. If some physical laws already permit to describe some cracking propagation cases, other phenomena such as brittle rupture are unfamiliar. Moreover cracking of wall pressure vessel has to be coupled with fluid discharge.

2. Case STUDY: Bordes accident (09/05/2000) [2]

2.1 Context elements

This accident involved gas cylinders explosions (525 butane 13 kg bottles, 35 butane 6 kg bottles, 140 propane 13 kg bottles, 77 propane 35 kg bottles). Early in the morning, a 777 gas cylinders carrying truck was delivering a factory. The driver noticed that one of the towing tires was in fire. After unsuccessfully attempting to put out fire, he went back for help. The first bottles, exposed to the flames heat, exploded, causing even more bottles to explode. A security perimeter was put into place. The fire was only under control some 4 hours later. Nobody has been injured. A car wash, a depot, offices and some houses were damaged. Some bottle debris were found as far as one kilometer of the accident.

2.2 Analysis of fragments

Fragments and debris total mass was about 9400 kg, with 80% of the fragments within an 80 meters area around the truck. Ten more percents were lying between 80 and 100 meters around the truck. The fragments inventory is not complete, since some projectiles with unknown shapes and weights have clearly been witnessed flying. Some of them impacted further than 300 and 480 meters, a distance that corresponded to houses. Some fragments were even found at 8 or 900 meters.

Plotting the mass vs. the projection distance for long range fragments (over 100 meters) displays a graph (Figure 1), that can be divided into three zones:

- The most important ones in terms of samples involves 7 on the 10 listed fragments from distances between 150 and 250 meters and mass comprised between 2.5 and 8 kg.
- Two other fragments with a mass lower than 2.5 kg are to be found beyond a 250 meters zone. Other fragments were reported at further distances, but, unfortunately, without describing their shapes.
- An heavy single fragment (12 kg) was registered inside the 150 meters zone. So far, many debris laid inside this zone since it is close to the accident, but they generally result from fragments impacts on neighbor bottles, and, as such, are of few interest in the present research.

Table I: List of accidents with associated data. (ARIA data base [1], compiled by the BARPI ; and INERIS).

Place and year	**Type, capacity of the vessels**	**Used products**	**Causes of the accident**	**Resulting phenomena**	**Material damages**	**Human consequences**
Alma (U.S.) (1958)	80 m^3 cylindrical vessel	LPG (butane)	Overpressure	UCVE	?	1 dead 4 injured
Brinkley (U.S.) (1959)	Tank trailer 3 vessels (<60m^3)	LPG (butane)	Human mistake	BLEVE	Considerable	1 dead
Feyzin (France) (1966)	1200 and 2000 m^3 spheres	LPG (propane)	Human mistake	leak, inflammation, explosion, fragmentation	?	1 dead
Crescent City (U.S.) (1970)	Wagon	LPG	Sparks due to derailment	BLEVE	Wagon fragments at 500 m	66 injured
Saint-Amand (France) (1973)	Tank trailer	LPG (propane)	Leak due to road accident, ignition due to friction on ground	BLEVE	Truck projection on a house, propagating the fire	?
Kingman (U.S.) (1973)	75 m^3 tank wagon	LPG	Human mistake	Gas inflammation BLEVE	Wagon projection at 365 m; 5 buildings in fire	13 dead (operator and 12 firemen) 95 injured
Kurtkoy (Turkey) (1997)	aerosol cans and 10 t cylindrical vessel	LPG (butane)	Spark due to electricity return after power failure	Explosion of the drums and BLEVE of the vessel	Collars and cylinder heads projection as far as 80 m. Broken windows in a 500 m radius area	?
Qatar (1977)	23 000 t cryogenic vessel	LPG	Bad quality welds and insufficient maintenance	VCE	Totally destroyed factory; damages as far as 2 km	7 dead
Texas City (U.S.) (1978)	800 m^3 sphere	LPG (isobutane)	Overfilling and cracking on welded joint (leak)	BLEVE	Broken windows in a 3.5 km radius area	7 dead 10 injured
San-Ixhuatepec (Mexico) (1984)	4 spheres of 1600 and 2400 m^3, 48 cylindrical vessels	LPG	Rupture of a pipe under 24 bars	BLEVE and domino effects	Fragments further than 1200 m	500 dead 7000 injured
Asahikawa (Japan) (1988)	Recompression unit and filling device of gas cylinder	LPG	Procedure overriding resulting in leaking	Explosion (unknown cause of ignition) and fire	1 207 destroyed gas cylinders	3 dead 2 injured
Sydney (Australia) (1990)	Aerial vessels (160-148-88-31m^3), tank trailers, cylinders	LPG	Ignition source: electrical spark. An opened floodgate propagates a fire	Succession of BLEVEs	Shock wave felt at 3km; hundreds of small cylinders	?
(South Korea) Ulsan (1990)	Vessel	LPG (butane)	static electricity discharge	Protection system fire leakage that leads to fire and vessel explosion	?	?
Sainte Sophie (Canada) (2001)	Gas cylinders with capacities up to 180 kg	LPG (propane)	Short circuit	BLEVE	All the vessels (2~300) and a tank trailer	0 injured

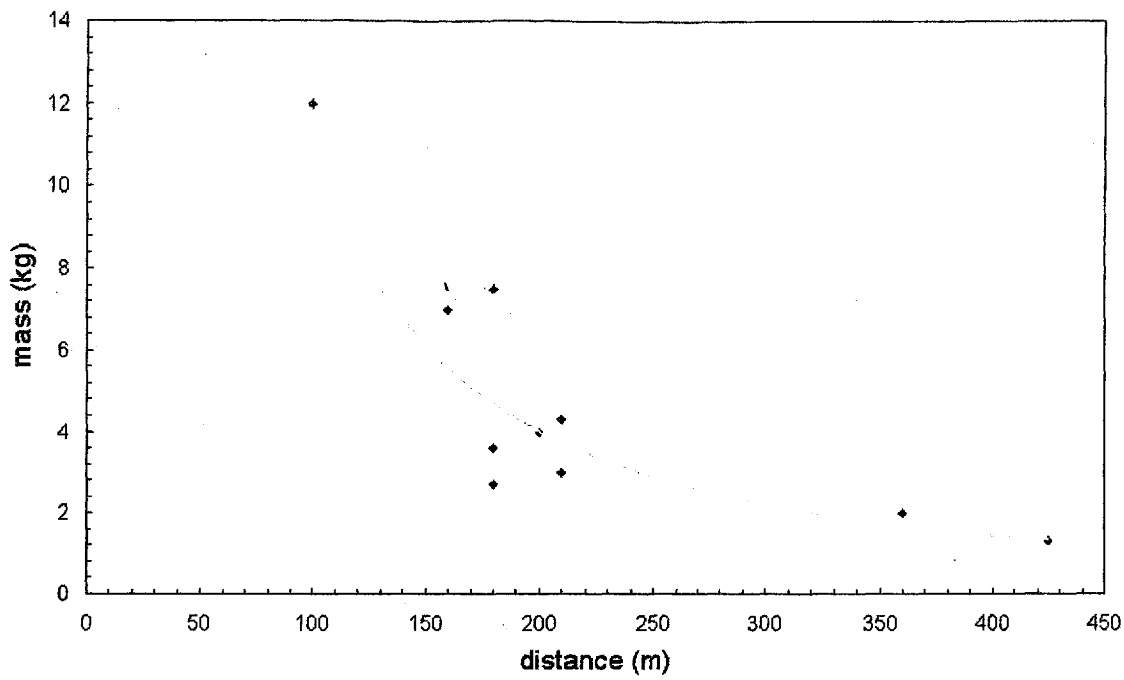

Figure 1. Fragments mass vs. falling distance (Bordes accident).

The biggest fragments were found at a distance less than 180 meters: they result from the rupture of the enclosure into two pieces, and, as such, are representative of a vessel ductile fracture.

Due to their shape, flat fragments have fallen much further. In general, they consist in smaller debris (1 to 4 kg) created by seemingly brittle bursts of vessels.

The last kind of fragments to be find were security designed parts like flanges and heads, with a mean mass of 2 kg. They fell at very variable distances between 180 to 350 meters, depending on the stiffness of the pressure rise by the time they were activated.

2.3 Explosion of gas cylinders

LPG bottles that exploded during this accident are commonly used bottle, viz. when full, LPG occupies about 85 % of the space inside the cylinder and so, liquid phase is in equilibrium with its vapor phase, that determines the pressure inside the enclosure.

Depending on how a liquefied gas bottle is heated, two main processes are susceptible to produce a capacity burst:

- If the wall in contact with the gas phase is directly heated by flames, convective heat transfers between gas and wall are insufficient to counterbalance the incoming heat flux. Wall temperature will locally increase, causing a diminution of its mechanical resistance. The drop off, in conjunction with the pressure rise, can be such that the wall can not resist the pressure inside the enclosure and fails. This phenomenon results in a fracture, that can be the initiator of a burst for brittle materials, and the precursor of a breach for ductile ones. When the result is a breach in the gas part, a torch fire can be created. Otherwise, the burst may produce a fireball with fragments projections.

- When the liquid phase is directly heated or when the whole capacity is surrounded by flames, the input flux on the wall is almost totally transferred to the liquid phase, and contributes to the phase change from liquid to vapor, following the saturated vapor curve. Since for liquefied gas, the vapor phase specific volume is generally about thousand times the liquid phase specific volume, this vaporization results in a huge pressure rise inside the bottle, that can exceed the wall resistance. Moreover, if the capacity wall is surrounded by fire, wall mechanical resistance of the gas side can fall down at the same time. Depending on both pressure rise slope and wall material nature, the response of the enclosure can consist in a burst or in the split of the vessel.

LPG bottles have security flanges that are designed to liberate the bottle head for high pressures, and thus help reducing the consequences of the rupture. Under the effect of the gas pressure, the part sealing the nose of the tap distends, bursts and liberates the gas. So the pressure drops inside the enclosure, causing more liquid to vaporize. All this gas ignites and provokes the ejection of the whole set: flange, tap and cap.

As told above in Par. 2.2, several tens of fragments corresponding to that event were found after Bordes accident.

3. Modeling of pressure metallic enclosures failures

Bordes accident illustrates the complexity of pressure vessel rupture phenomenon, and the various consequences in terms of fragmentations and projections.

- Before its failure, an enclosure can suffer high deformation that will absorb part of the phenomenon energy;
- Wall cracks can also start and propagate, causing an internal pressure discharge, and finally stop;
- Fragments shapes are dependent of the bottle burst.

These considerations point out the static or dynamic aspect of the rupture, that is linked to the pressure evolution. Consequently, depressurization during the enclosure rupture has to be taken in account. This clearly indicates the importance of fluid structure coupling.

3.1 Global description of crack and depressurization modeling

Even if several different models describe pressure vessel failure, few models present a global approach of the problem. Many of them insist on the mechanical point of view, others on the depressurization, few on the coupling of both phenomena.

Many different representations of crack propagation have been developed. The basis of crack development models takes place on the use of usual failure criteria. Thus the difference between those models mostly stands on the diversity of these criteria. As examples, some of them display the maximal stress criterion in which the crack is supposed to propagate perpendicularly to the maximal hoop stress. Some other use the minimal strain density where the crack propagates in the direction of the minimal strain density energy. Other criterion of interest in the crack propagation models is the maximal energy release rate, in which the crack is suppose to develop in direction of the highest energy release value, and so on... The Crack Opening Displacement where the development of crack is considered linked to its width as also to be mentioned in this review.

Finite elements can handle crack propagation with two methods as described by [3]:

- The first one consists in adding a relaxation node that corresponds to a crack tip;
- In the second, a zone is creating around a note to delimit the crack tip.

Studies [4-5] using finite element method emphasize the influence of the characteristic length and the mesh resolution: the average crack speed increases for finer mesh while it decreases for increasing value of material characteristics such as length, the nature of mesh influences prediction of the crack growth.

To reduce the importance of these parameters, [6] proposes a different method: it consists in determining the asymptotic solution of stresses near the crack tip, since the knowledge of stress and displacement field near crack tip are useful for fracture criteria.

Another method used to determine stress field in plastic zone, near the crack tip, is the slip-line theory: [7] obtained interesting results with this method.

All these different models show that the mechanical aspect of failure can be well described. However, if crack is considered as the main aspect of pressure vessel failure, it shall not be separated from depressurization: as internal pressure evolves with crack propagation, it is essential to study this phenomenon.

Depressurization is also characterized by the fluid state: as fluid can either be gaseous or liquid, (or in a liquid-vapor equilibrium), the discharge can either be a single or double phase flow.

Among the different models that describe depressurization, most of them try to calculate the discharging time of the bottle. To do that, some of them take the fluid state as a parameter while others only consider a monophasic outflow. The other input parameters can be the kind of breach (varying or constant) as well as the pressure and the temperature inside the bottle. The output data can consist in the discharging time, and also the pressure and temperature evolutions inside the bottle.

The simplest model, elaborated by [8], consists in calculating gas temperature and pressure for a constant flow. On the opposite side, analytical models from [9] involve a fluid, liquid or gas, that can changeably flow at either sonic or subsonic speed.

3.2 Baum depressurization model

So far, different models have been exposed, that only deal with crack propagation and/or depressurization. More in relation with Bordes accident are the Baum models [10-11]. They depict a mixed process where a variable breach opening results in the propulsion of fragments behaving like missiles or rockets.

Basis of these models are to be found in the several studies on rocket velocity and fragments conducted by Baum.

At the beginning of a circumferential crack, Baum's models depict the capacity as a cylinder containing either a gas or a diphasic gas liquid medium at internal pressure P (Figure 2a, 2b).

Breach opening is introduced through the first steps of rocket displacement. The breach area is defined as the space between the flying part and the remaining one. An opening time is calculated as the time necessary to fully open the breach area, that takes place when rocket displacement has reached half the enclosure radius. Thus, considering internal pressure much higher than external pressure, the minimum opening time is equal to (for rupture at one end of the vessel, Figure 2a):

$$t_{\lim} = \left(\frac{M}{P\pi\ r} \right)^{1/2} \tag{1}$$

where M is the mass of rocket, P is the internal pressure, r pressure vessel radius.

As above mentioned, this model cannot be compared with a crack propagation model, since no stress and only displacement is involved in the expression of breach area development. However, Baum's model is of great interest with regard to the idea of coupling, it introduces: mass flow rate evolves with the breach area.

3.3 Fracture and depressurization coupling models

A notion exposed in Baum's model is breach opening time: time is an important characteristic of pressure vessel rupture, since crack propagation time and gas discharge time are in competition to influence pressure vessel behavior. Indeed, discharge can be finished before failure of vessel has been reached and reciprocally, crack propagation can stop before the end of fluid discharge. So, to be realistic, a model has to include a crack propagation law in addition to a depressurization law.

3.3.1 Lenclud and Venart coupling model

On the basis of experiments, Lenclud and Venart [12] developed a crack opening model for a single phase discharge and studied its influence on crack speed depressurization. As previously mentioned, they also reported various two phase flow models. They exposed models for every stage of the phenomenon as well, viz. crack opening displacement and depressurization. For this last step, single or two phase flow can be considered.

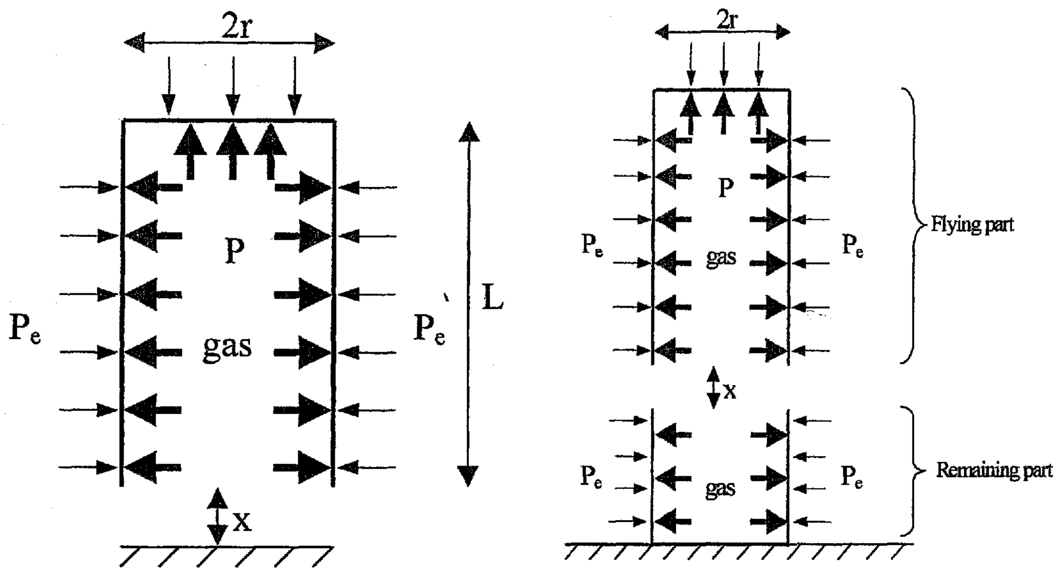

Figure 2a. Rupture of a gas-pressurized vessel.

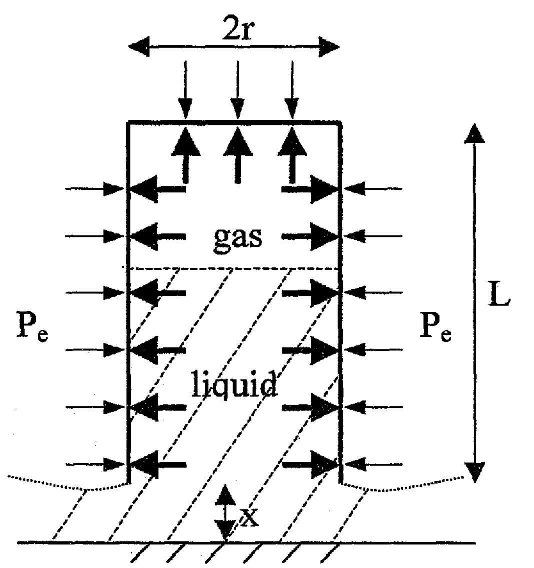

Figure 2b. Rupture of a high pressure liquid storage vessel.

The crack opening in the first step of rocketing fragments.

They consider the crack opening as the result of both elastic and plastic displacements.

Total crack opening is supposed to be the summation of both elastic and plastic displacement. Thus the crack area is given by:

$$A = \pi \, a \, b = \pi \, a^2 \left(\frac{1}{C} + \frac{\Delta}{2a} \right) \tag{2}$$

where a is the half crack length, b is the half crack width, C represents the plastic component $\left(\frac{a}{w} = C\right)$ (Fig. 3b) and Δ the elastic one (Fig. 3a).

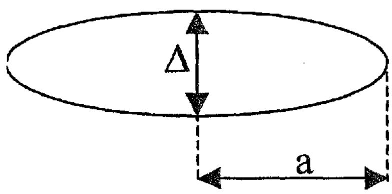

Figure 3a. Elastic deformation.

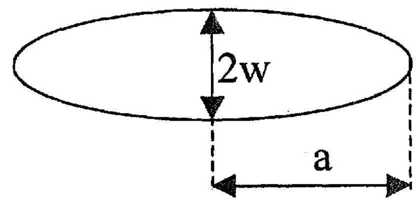

Figure 3b. Plastic deformation.

Crack velocity is then introduced in the latter analytical expression. Crack velocity results from high speed cinematography experiments. From the authors analysis, crack propagation is divided into steps, that may be single or double.

As an example, the crack length 2a can be expressed at each time step as:

$$\begin{aligned} 0 < t < t_1 &: \quad 2a = v_1 \times t \\ t_1 \le t < t_2 &: \quad 2a = v_2 \times t + C_2 \\ t \ge t_2 &: \quad 2a = 2l_f \end{aligned}$$

with v_1, v_2 crack velocity, C_2 experimentally determined constant , and t time.

Depressurization in this model is asserted to be best represented by a single shocked phase flow.

3.3.2 Erdogan coupling model

A more elaborated model coupling fracture dynamics and fluid mechanics has been established by [13]: it represents a gas pressurized cylindrical tank rupture. Erdogan noticed the relevant points of the failure phenomenon that are to be considered:

- The possibility for a crack to stop or to result in a catastrophic failure depends on the nature of the fluid discharge due to the internal pressure evolution;
- The distinction between brittle and ductile failure.

He then insisted on the difficulty to estimate the boundary conditions at the breach. Moreover this estimation is complicated by the crack propagation. To simplify the problem, he proposed the following assumptions:

- For shell analysis, inertia effects are neglected, provided that crack velocity remains below approximately one fourth the shear wave velocity of the shell material, and the problem is considered as quasi-static;
- Gas is considered as ideal with constant specific heat;
- Pressure drops in the container are supposed slow: the gas dynamics problem is treated as one-dimensional;
- The discharge is sonic at breach;

- The crack opening is instantaneously achieved and approximated by an ellipse of which area is:

$$A(t) = \pi\, a^2 p \left[\frac{2 \times r}{e \times E} + \frac{1.47 a^2}{e^2 \times E} \right] \tag{3}$$

with a half crack length, r pressure vessel radius, p internal pressure, e wall thickness, E elastic modulus (see Figure 4 for initial pressure vessel conditions).

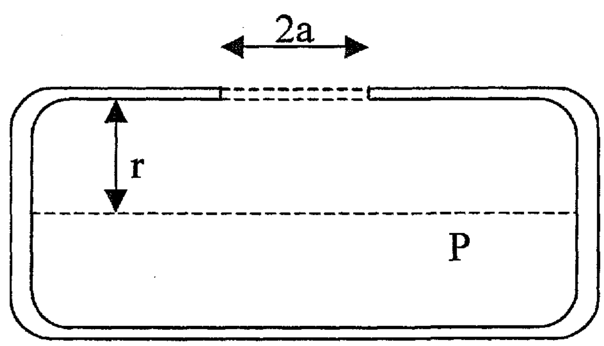

Figure 4. Initial pressure vessel conditions.

Given these hypothesis, the main aspect of his model stands on the choice of a dynamic rupture criterion. Such criterion relies both the dynamic nature and the crack driving force. Erdogan proposed to express crack acceleration and velocity as a function of the crack driving force. Still the crack driving force can be defined using different expressions, that are dependent on the nature of crack, and consequently, brittle and ductile fractures are to be distinguished.

According to Erdogan, the most realistic parameters defining the crack driving force for a brittle fracture is the stress intensity factor K-K_c, or the strain energy release rate G-G_c.

Ideally brittle materials (with no inertia effect) see their dynamics fracture criterion as a relationship between crack velocity $\frac{da}{dt}$ and K:

$$\frac{da}{dt} = \begin{cases} \sum_{1}^{N} d_n (K^2 - K_C^2)^n, for \quad K > K_C \\ 0 \quad for \quad K < K_C \end{cases} \tag{4}$$

with d_n experimentally determined constants.

However, neither instantaneous velocity changes nor inertia effects can be modeled with this expression. Thus this first criterion (crack velocity) must be complemented a second one (crack acceleration $\frac{d^2a}{dt^2}$):

$$\frac{d^2a}{dt^2} = \begin{cases} b_1(K - K_C) & for \;\; K > K_C \\ b_1(K - K_C) - b_2(K - K_C)^2 & for \;\; K < K_C \end{cases} \tag{5}$$

or

$$\frac{d^2a}{dt^2} = \begin{cases} b_3(K^2 - K_C{}^2) & for \;\; K > K_C \\ b_3(K^2 - K_C{}^2) - b_4(K^2 - K_C{}^2)^2 & for \;\; K < K_C \end{cases} \tag{6}$$

with b_n experimentally determined constants.

The second formulation (eq. (6)) is based on strain energy release rate, but instead of using the G parameter, K^2 expression is used, since it is assumed that $G \sim K^2$.

As such, K appears to be the main parameter. The knowledge of the stress intensity factor is sufficient determine crack velocity and acceleration.

For a pressurized cylindrical shell suffering an axial crack, Erdogan approximated the stress intensity factor by:

$$K = \frac{P \times r}{e} \times \sqrt{\pi a}\; A(\lambda) \tag{7}$$

with:

$$A(\lambda) = \begin{cases} 0.5\,\lambda + 0.6 + 0.4\, e^{-1.25\lambda} & for \;\; \lambda \leq 5 \\ 1.761\sqrt{\lambda - 1.9} & for \;\; \lambda > 5 \end{cases} \tag{8}$$

and:

$$\lambda = \left[12(1 - \upsilon^2\right]^{1/4} \frac{a}{\sqrt{r \times e}} \quad \text{(shell parameter)} \tag{9}$$

This brittle fracture model proposed by Erdogan includes the main crack characteristics:

- A crack driving force (the well-known stress factor intensity);
- An expression of crack evolution (velocity, acceleration) and the special stress intensity factor calculated for cylindrical vessel.

In addition, this model is provided with experimentally determined constants.

For ductile fractures, a different crack driving force is introduced to take into account the ductile behavior of the material: the "resistançe pressure" (p_r)

$$p_r = p_y\left[\, n + (1 - n)\, e^{-m\lambda} \right] \tag{10}$$

where $\quad p_y = \frac{e \times \sigma_y}{r} \qquad \sigma_y = \sigma_{ys}(1 + \beta)$

with

n, β ,α constants ($0 < n < 1$ / $0{,}05 < \beta < 0.15$ / $\alpha > 0$)

σ_{ys} represents the yield strength of the material, σ_y the flow stress and p_y pressure corresponding to a fully "yielded cylinder": here, parameters characterizing yielding are included in formulas.

So the dynamic fracture criterion can be written as:

$$\frac{d^2a}{dt^2} = \begin{cases} c_1(p-p_r) & for \quad p > p_r \\ c_1(p-p_r) - c_2(p-p_r)^2 & for \quad p < p_r \end{cases} \tag{11}$$

or

$$\frac{d^2a}{dt^2} = \begin{cases} c_3(p^2-p_r^2) & for \quad p > p_r \\ c_3(p^2-p_r^2) - c_4(p^2-p_r^2)^2 & for \quad p < p_r \end{cases} \tag{12}$$

with c_n experimentally determined constants.

These equations are naturally solved numerically. End of calculations is either consecutive to a nil crack velocity with the crack length inferior to a limit (a<0,8 L/2) or to a crack length that reaches this limit.

Erdogan's models provide a good agreement with reality, for some simulated trends are conform to those expected. Thus, results of the quasi-brittle model are in accordance with a real brittle behavior: no crack stop has been numerically observed, and crack velocity was still increasing, even after crack length reached 80% of the total cylinder length.

The cylinder length is an important parameter of the ductile model, that seems to strongly influence crack arrest. Actually, the longer the cylinder is, the more crack would tend to stop before reaching the total cylinder length. Obviously, the value of constants also influences quantitatively the results. As for shell parameter, the choice is not a problem since it is defined from crack length, cylinder radius and length.

However, even if few studies consider the coupling between fracture and gas dynamics, and if Erdogan's results are interesting, his study is not exempted from reproach. The most evident is the lack of comparison with experiments: if his model seems to be qualitatively good (the description of failure behavior is realistic), quantitatively there is no reference. For instance, different results are presented for different constants, but Erdogan does not mention which of them would give the best correspondence with reality.

4. Conclusion

Post accidental analysis of pressurized vessels ruptures have compiled lots of data on their consequences, that help understanding the main causes of their failures. However, the coupling between the mechanical aspect of rupture and depressurization remains largely unexplored, especially for a smooth quantification of the effects in the environment of the capacity.

So, there is still a place in research to refine these aspects, with experiments providing relations between parameters such as pressure, time, brittle point of different materials, temperature... This experimental work could supply data (material behavior, crack propagation and discharge time...) for simultaneous numerical model development, following the approach initiated by Erdogan.

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